

Three-dimensional cavity-based graphene superconducting quantum circuits in two-circuit joint-readout architectures

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We construct a series of graphene-based superconducting quantum circuits and integrate them into three-dimensional (3D) cavities. For a device exhibiting single-qubit behavior, we demonstrate flux-tunable qubit transition, with a relaxation time $T_1 \approx 48$ ns measured in one cooldown at a reduced qubit frequency of 3.65 GHz, and a separate power-broadening-based lower bound $T_2^* \gtrsim 17.63$ ns at the sweet spot in an earlier cooldown at $f_q \approx 8.07$ GHz. By coupling the device to cavities with different resonant frequencies, we access multiple qubit-cavity coupling regimes, enabling the observation of vacuum Rabi splitting and flux-dependent spectral linewidths. In a two-circuit device consisting of a superconducting quantum interference device (SQUID) and a single junction, power-dependent measurements reveal a two-stage dispersive shift. By flux tuning the cavity frequency at different readout powers, we attribute the first shift to the fixed qubit and the second to the SQUID qubit, indicating successful coupling between the two circuits and a single cavity mode. Our study demonstrates the flexible coupling achievable between two-dimensional (2D)-material-based flux-tunable superconducting circuits and 3D cavities, and paves the way toward constructing multicircuit 3D transmonlike devices from 2D materials.

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I. INTRODUCTION

Integrating low-dimensional materials into circuit quantum electrodynamics devices has attracted increasing interest due to their wide range of potential applications [1–17]. In particular, substantial efforts have focused on replacing the insulating tunnel barrier in Josephson junctions (JJs) with low-dimensional materials, enabling the resulting superconducting qubits to inherit their unique properties [1–3,6,11,12]. Early studies have demonstrated the successful implementation of InAs nanowires, two-dimensional electron gases (2DEGs), and graphene in gate-tunable transmons

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(gatemons) [1–3,6,7], flux-tunable transmons [7,18], and transmons tunable by both gate and flux [19]. More recently, weak links based on InAs nanowires and InAs 2DEGs have been integrated into gate-tunable fluxoniums, enabling smooth tuning between heavy and light fluxonium states [20,21]. The most recent advances further report transmons based on NbSe₂/WSe₂/NbSe₂ vertical JJs [22], graphene charge qubits [23], and weakly anharmonic NbSe₂ qubits [24]. While most studies follow the mainstream approach of superconducting qubits based on 2D coplanar waveguides, which offer advantages for scalability, 3D transmons provide several benefits that their 2D counterparts cannot. First, the external quality factor, cavity decay rate κ , and qubit-cavity coupling strength g can be conveniently tuned by adjusting the readout pin length and the qubit's position inside the cavity [25]. Second, by loading qubits into cavities with different resonant frequencies, the detuning between the qubit frequency maximum and the cavity resonance can be varied, thereby enabling access to different coupling regimes. Third, the use of a 3D cavity simplifies the fabrication process, which in turn improves the yield of devices incorporating new materials. The first two are not achievable with a 2D transmon once its planar readout resonators, capacitors, and JJs have been fabricated. In addition, the capacitor pads in 3D transmon can be used as a bond pad in dc transport, allowing comparison between dc and microwave measurements on the same device [26].

In this work, we present a series of graphene-based superconducting circuits in a two-circuit joint-readout configuration coupled to 3D cavities. By loading the same devices into different cavities, thereby varying the detuning between the maximum qubit frequency and the cavity resonance, we access distinct coupling regimes across multiple cooldowns. We construct a graphene single-qubit device with a flux-tunable qubit transition, demonstrating vacuum Rabi splitting in the strong-coupling regime and flux-dependent spectral linewidths in the dispersive regime. In another device comprising a superconducting quantum interference device (SQUID)-based circuit and a single-junction circuit, we observe distinct two-stage power-dependent dispersive shifts when coupling them to two different cavities. Flux tuning of the cavity responses and the onset power of the dispersive shifts further reveal that the first dispersive shift originates from the single-junction circuit, while the second is associated with the SQUID circuit. Our results highlight the potential of 2D materials for realizing multicircuit 3D transmon architectures, enabling the possibility of joint readout and the study of interactions between distinct 2D-material-based superconducting circuits.

II. DEVICE FABRICATION AND MEASUREMENT SETUP

Figure 1 shows the optical micrograph of one of the two devices investigated in this study. Our 3D cavity, fabricated from copper as shown in Fig. 1(a), provides good thermal conductivity while allowing magnetic flux to penetrate. The graphene-based superconducting quantum circuits investigated in this work are all designed in a two-circuit configuration. We present data from a two-SQUID device (device 1; see Fig. S1 in the Supplemental Material [27]) in which one SQUID was nonfunctional and exhibited no cavity response, as well as from a device comprising one SQUID and one single JJ (device 2). Figure 1(b) shows a micrograph of device 2, where the SQUID-based qubit (Q1) is equipped with a pair of bigger capacitor pads ($590\text{ }\mu\text{m} \times 320\text{ }\mu\text{m}$) while the single-JJ qubit (fixed qubit, Q2) is equipped with smaller capacitor pads ($96.76\text{ }\mu\text{m} \times 400\text{ }\mu\text{m}$). Figures 1(c) and 1(d) show micrographs of Q1 and Q2, respectively, while Fig. 1(e) presents an effective schematic illustrating how the two circuits are coupled to one resonator. Both the SQUID and the single JJ are realized using NbTi-graphene-NbTi junctions fabricated with edge-contact techniques [32]. The design parameters and details of the device fabrication process are provided in Sec. I of the Supplemental Material [27].

The measurement schemes employed in this work are illustrated in Fig. S2 of the Supplemental Material [27]. The devices were mounted in a two-port 3D copper cavity, with Q1 located at the center of the chip and aligned with the center of the cavity chamber. The sub-miniature version A (SMA) port located near the center of the cavity, where the chip is positioned, is used for readout, while the off-center SMA port serves as the drive port. Additional details on the 3D cavity

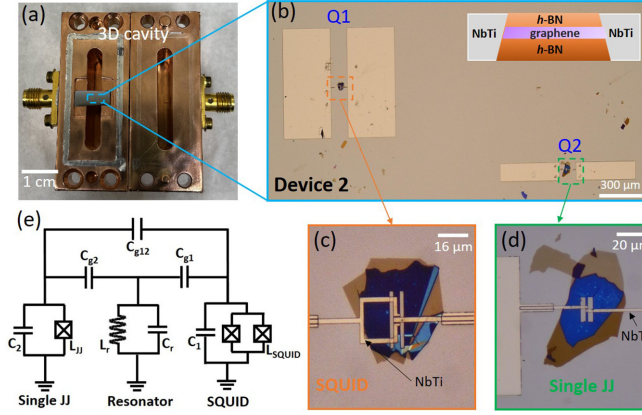


FIG. 1. Optical micrograph of the two-circuit graphene-based superconducting quantum circuit coupled to a 3D copper cavity. (a) Image of qubit chip mounted in the 3D copper cavity. (b) Optical micrograph of device 2, consisting of a SQUID-based circuit (Q1) and a single-JJ circuit (Q2). The inset shows the hBN/graphene/hBN sandwich structure with NbTi edge contacts for the junctions shown in panels (c) and (d). (c) Optical micrograph of the SQUID circuit consisting of graphene and superconductor NbTi. The design parameters can be found in Fig. S1(g) of the Supplemental Material [27]. (d) Optical micrograph of the single-JJ circuit. The design parameters can be found in Fig. S1(g) of the Supplemental Material [27]. (e) Schematic of the circuits (qubits) coupled to a microwave resonator. Q1 is coupled to the resonator via the capacitance C_{g1} , while Q2 is coupled via C_{g2} . Q1 is coupled to Q2 via C_{g12} .

calibration and measurement setups can be found in Ref. [26] and in Sec. II of the Supplemental Material [27].

III. DEVICE CHARACTERIZATION AND RESULTS

We first characterize the SQUID-based qubit (Q1) in device 1, as shown in Figs. S1(b) and S1(e) of the Supplemental Material [27]. This device was measured in different cavities across multiple cooldowns, as summarized in Sec. III of the Supplemental Material [27]. Here, we begin with the data obtained from cooldown 2. Figure 2(b) presents the measured S_{21} through the cavity readout port as a function of readout frequency and power at zero magnetic flux [labeled (b) in Fig. 2(a)]. Power-dependent cavity response provides a useful check for the presence of a qubit, as the cavity resonance shifts toward the qubit frequency at sufficiently high readout powers [33]. At low power (-50 dBm), the cavity exhibits a dip at $f_r = 6.02937$ GHz. When the power exceeds -30 dBm, the qubit becomes saturated, and the cavity shifts to its bare resonance $f_{\text{bare}} = 6.0558$ GHz, accompanied by a narrower linewidth. The readout power required for the cavity to enter this high-power regime is characterized by the critical photon number $\bar{n}_{\text{crit}} \approx \frac{\Delta^2}{4g^2}$, where $\Delta = 2\pi(f_{\text{bare}} - f_q)$ is the detuning between the bare cavity frequency f_{bare} and the qubit frequency f_q , and g is the qubit-cavity coupling strength [34–36]. Figure 2(c) shows the power-dependent cavity response measured at another flux bias, labeled (c) in Fig. 2(a), where f_q is minimized to approximately zero. As expected, with increased detuning Δ compared to the case in Fig. 2(b), the onset power for the high-power regime also increases to approximately -25 dBm. Next, we perform flux tuning of the cavity response by measuring S_{21} at a low readout power (-50 dBm) while sweeping the dc current applied to the superconducting coil. As shown in Fig. 2(a), the flux-modulated cavity response bends both upward and downward relative to the bare cavity frequency, indicating that f_q crosses f_{bare} due to the tunability provided by the functional SQUID. In the vicinity of the resonant limit $f_q \approx f_{\text{bare}}$, the qubit and resonator hybridize, resulting in an avoided crossing as shown in Fig. 2(d). The split cavity peaks at $f_q \approx f_{\text{bare}}$ are known for vacuum Rabi splitting, indicating that

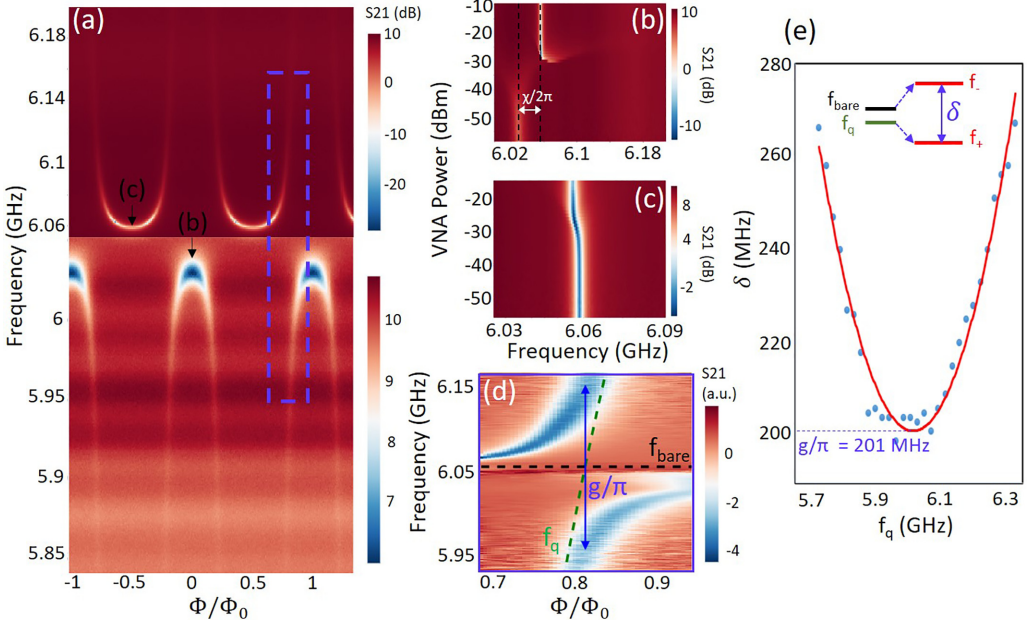


FIG. 2. Flux- and power-dependent cavity response (S_{21}) of the single-qubit device (Q1 in device 1) in cooldown 2. (a) Flux modulation of the cavity frequency for device 1. Note that the upper part and the bottom part were measured separately in order to improve the visibility of cavity response. The arrows indicate the flux bias points where the power-dependence measurements in panels (b) and (c) were performed. The dashed rectangle denotes the flux and frequency ranges displayed in panel (d). (b) Power-dependence measurement of device 1 at the zero-flux point (sweet spot) labeled (b) in panel (a). (c) Same as panel (b), but measured at the other flux point, where f_q attains its minimum, as labeled (c) in panel (a). (d) Enlarged measurement of the blue rectangular region indicated in panel (a), showing a vacuum Rabi splitting when the qubit frequency aligns with the bare cavity frequency. Note that the data have been mean subtracted and smoothed along the flux axis for clarity. (e) Frequency splitting between the hybridized qubit-cavity states, as a function of f_q , as extracted from panel (a).

the device operates in the strong coupling regime, where the coupling strength g exceeds both the qubit and cavity decay rates (γ and κ). The frequency of the hybridized qubit-cavity states can be written as $f_{\pm} = [f_q + f_{\text{bare}} \pm \sqrt{(f_q - f_{\text{bare}})^2 + 4(g/2\pi)^2}]/2$ [6]. Figure 2(e) shows the splitting $\delta = f_+ - f_-$ as a function of f_q , from which we can extract the coupling strength $g/2\pi = 100.5$ MHz through fitting. Note that the extracted coupling strength g agrees well with simulations and remains reasonably consistent for the same device loaded into different cavities across multiple cooldowns (see Secs. III and V of the Supplemental Material [27]).

With the obtained g , we can estimate the maximum qubit frequency $f_{q,\text{max}}$ from the dispersive shift $\chi/2\pi \approx 26.4$ MHz between the low-power (f_r) and high-power (f_{bare}) cavity frequencies [Fig. 2(b)], using $\chi = g^2/\Delta$ and $\Delta = 2\pi(f_{q,\text{max}} - f_{\text{bare}})$, yielding $f_{q,\text{max}} \approx 6.438$ GHz. The symmetric SQUID qubit can therefore be modeled as $f_q \approx f_{q,\text{max}}\sqrt{|\cos(\Phi)|}$ [26], which we overlay on the flux-modulated cavity response in Fig. 3(a). To verify the modeled qubit spectrum, we performed two-tone spectroscopy in continuous-wave mode, where a second continuous drive tone was applied to the cavity in addition to the readout tone. The measurement was carried out by recording S_{21} at the cavity's resonant frequency for different magnetic flux values while sweeping the drive-tone frequency. When the drive tone was on resonance with qubit frequency f_q at each flux point, a peak in the cavity response was observed, yielding a flux-tunable qubit transition spectrum as shown in Fig. 3(b). The spectrum near the bare cavity frequency ($f_{\text{bare}} = 6.0558$ GHz) is distorted because the drive tone, being close to the cavity resonance, strongly excites the cavity mode and saturates

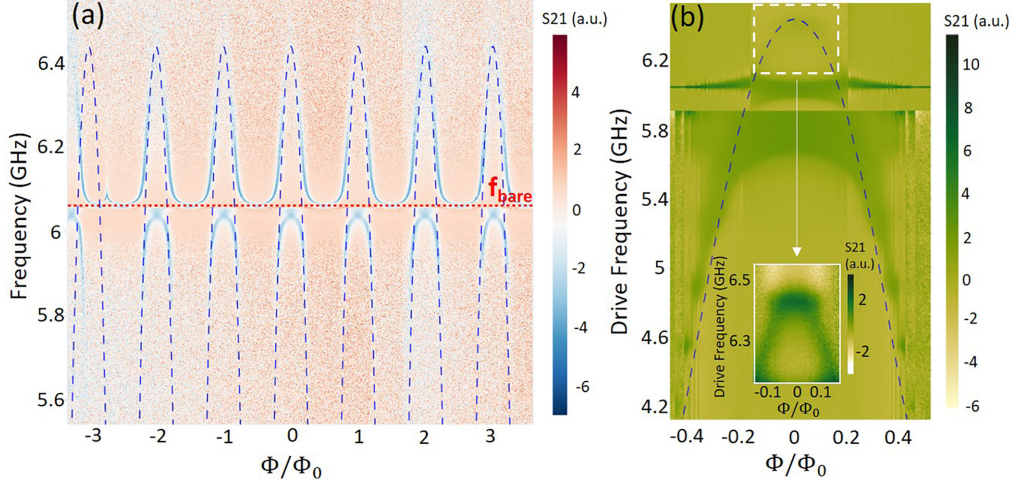


FIG. 3. Two-tone qubit spectroscopy of device 1 in cooldown 2. (a) Flux-dependent cavity response with the qubit frequency superimposed. Note that the data have been mean subtracted for clarity. The dashed line indicates the inferred qubit frequency $f_q \approx f_{q,\max} \sqrt{|\cos(\Phi)|}$, with a maximum value $f_{q,\max} \approx 6.438$ GHz as mentioned in the main text. (b) Two-tone measurement of the qubit transition as a function of applied flux Φ for device 1. The readout power was fixed at -50 dBm. The measurement was performed with two different drive powers: 15 dBm for the lower part of the spectrum, where f_q is far detuned from f_{bare} , and -13 dBm for the upper part, where f_q is close to f_{bare} . The spectrum is strongly distorted when the drive frequency approaches the bare cavity frequency ($f_{\text{bare}} = 6.0558$ GHz). To resolve the maximal qubit frequency, an enlarged measurement of the region indicated by the white dashed rectangle is performed and shown in the inset.

the readout signal. Therefore, a fine scan excluding this range and using low drive power (-13 dBm) was performed to accurately determine $f_{q,\max}$, as shown in the inset of Fig. 3(b). The obtained $f_{q,\max} \approx 6.43$ GHz is in excellent agreement with the estimated value based on g and dispersive shift.

Next, we examine the flux dependence of the spectral broadening, which reflects the qubit coherence time T_2^* [4,37,38]. The spectrum in Fig. 3(b), however, is unsuitable for this analysis because of its distortion around f_{bare} . In contrast, during another cooldown of the same device, shown in Fig. 4, the maximum qubit frequency lies well above f_{bare} , enabling us to extract an undistorted spectrum. This highlights a key advantage of 3D cavity devices, where switching cavities with different resonant frequencies can be employed to probe various qubit-cavity coupling regimes for the same device. Figures 4(a) and 4(b) show the power dependence and flux tuning of the cavity response, while Fig. 4(c) presents the qubit transition frequency as a function of flux, for this cooldown. Using $\chi = g^2/\Delta$, the dispersive shift $\chi/2\pi \approx 6.15$ MHz at $\Phi = 0$ [Fig. 4(a)] together with the maximum qubit frequency $f_{q,\max} \approx 8.068$ GHz [Fig. 4(c)] yields a coupling strength $g/2\pi \approx 111.3$ MHz. This value is consistent with the vacuum Rabi splitting result $g/2\pi = 100.5$ MHz from cooldown 2. The half linewidth of the $|0\rangle$ to $|1\rangle$ qubit transition (δ_{HWHM}) is related to the coherence time T_2^* and the relaxation time T_1 via $(2\pi\delta_{\text{HWHM}})^2 = (\frac{1}{T_2^*})^2 + n_s\omega_{\text{vac}}^2\frac{T_1}{T_2^*}$, where n_s is the average number inside the resonator, $\omega_{\text{vac}} = 2g$ is the vacuum Rabi frequency, and $n_s\omega_{\text{vac}}^2$ is proportional to the drive power [23,39]. The full width at half maximum (FWHM) of the spectral peak, extracted from Fig. 4(c), is shown in red in Fig. 4(d). Since the spectrum in Fig. 4(c) was measured under a finite drive power of 8 dBm (nonzero $n_s\omega_{\text{vac}}^2$), the observed spectral linewidths, which range from approximately 64.6 MHz at $\Phi = 0$ to 743.7 MHz at $\Phi = \pm 0.32\Phi_0$, provide a lower-bound range for T_2^* from 4.927 to 0.428 ns, using $T_2^* \approx 1/(2\pi\delta_{\text{HWHM}})$. We also performed a power-broadening measurement at $\Phi = 0$ (the sweet spot) and extracted an estimated $T_2^* \approx 17.63$ ns, as discussed in Sec. IV of the

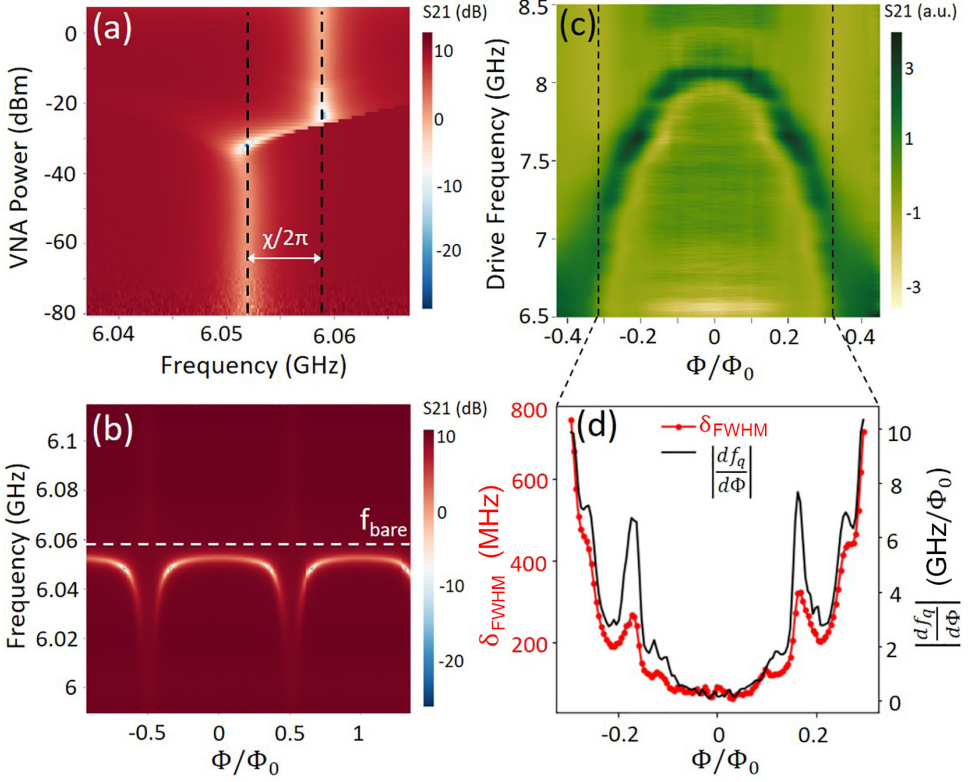


FIG. 4. Power dependence, flux tuning, and qubit spectroscopy for device 1 in cooldown 1. (a) Power-dependence measurements of device 1 performed at $\Phi = 0$ (sweet spot), with a dispersive shift $\chi/2\pi \approx 6.15$ MHz. (b) Flux modulation of the cavity frequency measured with a readout power of -60 dBm. The white dashed line indicates the bare cavity frequency at 6.059 GHz. (c) Two-tone measurement of the qubit transition as a function of applied flux, measured with a readout power of -60 dBm and a drive power of 8 dBm, showing a maximal qubit frequency $f_{q,\max} \approx 8.068$ GHz. The dashed lines denote the flux range for the analysis shown in panel (d). (d) Correspondence between the spectral linewidth (δ_{FWHM}) and the flux derivative of qubit frequency ($|df_q/d\Phi|$) extracted from the spectrum in panel (c). Note that both the spectral linewidth and the flux derivative of the qubit frequency exhibit abrupt changes at $\Phi \approx \pm 0.16\Phi_0$ and $\pm 0.27\Phi_0$, which originate from the kinks observed at the same flux values in the qubit spectrum shown in panel (c). We suspect that these features arise from coupling between the graphene-based SQUID circuit and energy modes of two-level systems, possibly located at the graphene/hBN, graphene/NbTi-edge-contact, or hBN/SiO₂ interfaces, or alternatively from spurious electromagnetic modes in the coaxial cables.

Supplemental Material [27]. The linewidth in Fig. 4(c) is narrowest at the sweet spot, where $df_q/d\Phi$ approaches zero, and becomes progressively broader away from the sweet spot as $df_q/d\Phi$ increases. In Fig. 4(d), we plot $|df_q/d\Phi|$ extracted from Fig. 4(c), and find a strong correlation between δ_{FWHM} and $df_q/d\Phi$. Since $df_q/d\Phi$ determines the sensitivity of the qubit frequency to low-frequency flux noise, this correlation suggests that T_2^* is dominated by qubit frequency fluctuations caused by low-frequency noise in our system (see discussions in Sec. IV of the Supplemental Material [27]) [40]. In addition, we performed time-domain pulse measurements to probe the qubit relaxation time in a later cooldown, where $f_{q,\max}$ is reduced to 3.65 GHz, yielding $T_1 \approx 48$ ns (see discussions in Sec. IV of the Supplemental Material [27]), consistent with values reported for graphene gatemon [2].

the qubit frequency for SQUID-based qubit is always higher than f_{bare} , as the second dispersive shifts are all toward higher frequency in all cooldowns (see the bottom panels of Fig. 5). Since the capacitor pad design of the SQUID circuit is identical in devices 1 and 2, we use the experimentally obtained coupling strength of $g/2\pi \approx 100$ MHz from device 1 as a design-based estimate, with a fractional uncertainty of around 12%. This is justified by the simulated $g/2\pi = 98$ MHz [26] being in agreement with all four cooldown values of device 1 to within $\sim 12\%$ (see Sec. III of the Supplemental Material [27]). Based on the second dispersive shift of 1.28 MHz at the sweet spot, extracted from Fig. S6(b) of the Supplemental Material [27] in cooldown 1, we therefore estimate $f_{q,\text{max}} \approx 13.86 (\pm 12\%)$ GHz for device 2. We further employ a simple geometric scaling argument as a consistency check for the inferred $f_{q,\text{max}}$. The junction width in device 2 ($3.5 \mu\text{m}$) is 3.5 times larger than that in device 1 ($1 \mu\text{m}$) [see Fig. S1(g) of the Supplemental Material [27]]. Given that $f_q \approx \sqrt{8E_J E_C}/h$ and $E_J = \Phi_0 I_C/2\pi$, we expect $f_{q,\text{max}}$ for device 2 to scale as $\sqrt{3.5}$ times that of device 1, yielding $\sqrt{3.5} \times 8.068 \text{ GHz} \approx 15.1 \text{ GHz}$, which is close to the value inferred from the coupling strength and dispersive shift. In Sec. V of the Supplemental Material [27], we simulated a coupling strength of $g/2\pi \approx 78.9$ MHz for the fixed qubit. Using this value, we further estimate the qubit frequency of the fixed qubit from the first dispersive shift observed in each cooldown. The corresponding discussions are provided in Sec. VI of the Supplemental Material [27]. It is worth noting that the linewidth of the cavity response after the first dispersive shift is reduced, as seen in the bottom panels, or by comparing the flux modulation data in the middle and upper panels of Fig. 5. This suggests that the fixed qubit acts as a loss channel for the cavity. Once the fixed qubit is saturated, the cavity effectively eliminates this lossy channel and regains a narrower linewidth. We have performed continuous-wave two-tone measurements on device 2. No flux-tunable qubit transition was detected, as was achieved in device 1, but potential fixed-qubit-related transitions are present, as discussed in Sec. VI of the Supplemental Material [27]. The fact that f_q of the SQUID-based qubit crosses the cavity periodically but does not form avoided crossings indicates that the device is not in the strong coupling regime (i.e., $\Omega \gg \gamma, \kappa$, where Ω is the qubit-cavity energy exchange rate and $\gamma(\kappa)$ is qubit (cavity) decay rate). This suggests a short coherence time for the SQUID-based qubit in device 2, with decay rate $\gamma > \Omega = g/\pi \approx 200$ MHz, corresponding to a coherence time $1/\gamma < 5$ ns, which may prevent us from resolving the qubit transition peaks in two-tone spectroscopy measurements. Comparing device 1 and device 2, the coherence properties of our qubits still exhibit device-to-device variations, likely arising from variations in the quality of the constituent graphene junctions. Nevertheless, the observation of two distinct dispersive shifts demonstrates that this two-circuit configuration can be extended to other 2D-material-based 3D transmon systems for joint readout, and may serve as a test bed for studying qubit-qubit interactions provided that qubit coherence is improved.

IV. SUMMARY

In this work, we have realized two graphene-based superconducting quantum circuits in joint-readout architecture: One device exhibits flux-tunable single-qubit behavior, while the other demonstrates two-circuit joint readout. For both devices, we placed them in cavities with different resonant frequencies, allowing us to access distinct coupling regimes between the qubits and the resonators. We present the first flux-tunable graphene transmon, with $T_1 \approx 48$ ns measured in one cooldown at a reduced qubit frequency of 3.65 GHz, and a separately obtained power-broadening-based lower bound $T_2^* \gtrsim 17.63$ ns at the sweet spot in an earlier cooldown at $f_q \approx 8.07$ GHz. The single-qubit device has demonstrated a strong coupling regime when the qubit frequency is tunable across the bare cavity frequency. In another cooldown, where the qubit frequency lies well above the bare cavity resonance, we observe a flux-dependent spectral linewidth, suggesting that T_2^* is limited by qubit frequency fluctuations induced by low-frequency flux noise. In the two-circuit device, we observed a distinct two-stage dispersive shift in the power-dependent measurements across four cooldowns, indicating variations in the detuning among the fixed qubit, the SQUID-based qubit, and the resonator when the device was placed in different cavities. The first dispersive shift is attributed

to the fixed qubit, while the second corresponds to the SQUID-based qubit, as supported by the flux-tunable cavity response observed after the first dispersive shift and the flux-dependent onset power of the second. In summary, we demonstrate the flexibility in qubit-cavity coupling achievable by 2D-material-based transmons when integrated with 3D cavities. The two-circuit architectures highlight the prospects for constructing multiqubit 3D transmon systems based on 2D materials for joint readout and control, provided that qubit coherence can be made sufficiently long [41].

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K.-L.C. conceived the project. Y.-H.L. designed the qubit layouts. C.-H.L., A. J. L., Y.-C.C., and S.-B.S. fabricated the devices under the supervision of K.-L.C. and C.-T.K. A.J.L., C.-H.L., and Y.-C.C. performed the measurements under the supervision of K.-L.C.. A.J.L. performed the HFSS simulations. K.-L.C. wrote the manuscript with input from all co-authors.

The authors declare no competing financial interests.

DATA AVAILABILITY

There are no publicly available research data or software supporting this manuscript. Requests for further information or data should be sent to the authors.

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- [1] J. G. Kroll, W. Uilhoorn, K. L. van der Enden, D. de Jong, K. Watanabe, T. Taniguchi, S. Goswami, M. C. Cassidy, and L. P. Kouwenhoven, Magnetic field compatible circuit quantum electrodynamics with graphene Josephson junctions, *Nat. Commun.* **9**, 4615 (2018).
 - [2] J. I.-J. Wang, D. Rodan-Legrain, L. Bretheau, D. L. Campbell, B. Kannan, D. Kim, M. Kjaergaard, P. Krantz, G. O. Samach, F. Yan, *et al.*, Coherent control of a hybrid superconducting circuit made with graphene-based van der Waals heterostructures, *Nat. Nanotechnol.* **14**, 120 (2019).
 - [3] L. Casparis, M. R. Connolly, M. Kjaergaard, N. J. Pearson, A. Kringhøj, T. W. Larsen, F. Kuemmeth, T. Wang, C. Thomas, S. Gronin, *et al.*, Superconducting gatemon qubit based on a proximitized two-dimensional electron gas, *Nat. Nanotechnol.* **13**, 915 (2018).
 - [4] A. Hertel, M. Eichinger, L. O. Andersen, D. M. van Zanten, S. Kallatt, P. Scarlino, A. Kringhøj, J. M. Chavez-Garcia, G. C. Gardner, S. Gronin, *et al.*, Gate-tunable transmon using selective-area-grown superconductor-semiconductor hybrid structures on silicon, *Phys. Rev. Appl.* **18**, 034042 (2022).
 - [5] C.-H. Lo, Y.-H. Chen, A. J. Lasrado, T. Kuo, Y.-Y. Chang, T.-Y. Hsu, Y.-C. Chen, G.-P. Guo, and K.-L. Chiu, Superconducting quantum circuits based on 2D materials, *SPIN* **13**, 2340021 (2023).
 - [6] T. W. Larsen, K. D. Petersson, F. Kuemmeth, T. S. Jespersen, P. Krogstrup, J. Nygård, and C. M. Marcus, Semiconductor-nanowire-based superconducting qubit, *Phys. Rev. Lett.* **115**, 127001 (2015).
 - [7] G. de Lange, B. van Heck, A. Bruno, D. J. van Woerkom, A. Geresdi, S. R. Plissard, E. P. A. M. Bakkers, A. R. Akhmerov, and L. DiCarlo, Realization of microwave quantum circuits using hybrid superconducting-semiconducting nanowire Josephson elements, *Phys. Rev. Lett.* **115**, 127002 (2015).
 - [8] J. Huo, Z. Xia, Z. Li, S. Zhang, Y. Wang, D. Pan, Q. Liu, Y. Liu, Z. Wang, Y. Gao, *et al.*, Gatemon qubit based on a thin InAs-Al hybrid nanowire, *Chin. Phys. Lett.* **40**, 047302 (2023).
 - [9] K.-L. Chiu and Y. Xu, Single-electron transport in graphene-like nanostructures, *Phys. Rep.* **669**, 1 (2017).
 - [10] F. E. Schmidt, M. D. Jenkins, K. Watanabe, T. Taniguchi, and G. A. Steele, A ballistic graphene superconducting microwave circuit, *Nat. Commun.* **9**, 4069 (2018).

- [11] X. Liu and M. C. Hersam, 2D materials for quantum information science, *Nat. Rev. Mater.* **4**, 669 (2019).
- [12] K. L. Chiu, Single electron transport and possible quantum computing in 2D materials, in *21st Century Nanoscience—A Handbook: Nanophotonics, Nanoelectronics, and Nanoplasmonics*, edited by K. D. Sattler (CRC Press, Boca Raton, FL, USA, 2020), pp. 13-1–13-48.
- [13] I. Siddiqi, Engineering high-coherence superconducting qubits, *Nat. Rev. Mater.* **6**, 875 (2021).
- [14] A. Antony, M. V. Gustafsson, G. J. Ribeill, M. Ware, A. Rajendran, L. C. G. Govia, T. A. Ohki, T. Taniguchi, K. Watanabe, J. Hone, *et al.*, Miniaturizing transmon qubits using van der Waals materials, *Nano Lett.* **21**, 10122 (2021).
- [15] J. Î.-J. Wang, M. A. Yamoah, Q. Li, A. H. Karamlou, T. Dinh, B. Kannan, J. Braumüller, D. Kim, A. J. Melville, S. E. Muschinske, *et al.*, Hexagonal boron nitride as a low-loss dielectric for superconducting quantum circuits and qubits, *Nat. Mater.* **21**, 398 (2022).
- [16] M. Tanaka, J. Î.-J. Wang, T. H. Dinh, D. Rodan-Legrain, S. Zaman, M. Hays, A. Almanakly, B. Kannan, D. K. Kim, B. M. Niedzielski, *et al.*, Superfluid stiffness of magic-angle twisted bilayer graphene, *Nature (London)* **638**, 99 (2025).
- [17] K.-L. Chiu, A. J. Lasrado, C.-H. Lo, C.-T. Ke, V. Mosallanejad, and Y.-H. Lin, Integrating quantum materials into superconducting qubits, *Mater. Quantum Technol.* **5**, 023002 (2025).
- [18] F. Luthi, T. Stavenga, O. W. Enzing, A. Bruno, C. Dickel, N. K. Langford, M. A. Rol, T. S. Jespersen, J. Nygård, P. Krogstrup, *et al.*, Evolution of nanowire transmon qubits and their coherence in a magnetic field, *Phys. Rev. Lett.* **120**, 100502 (2018).
- [19] T. W. Larsen, M. E. Gershenson, L. Casparis, A. Kringhøj, N. J. Pearson, R. P. G. McNeil, F. Kuemmeth, P. Krogstrup, K. D. Petersson, and C. M. Marcus, Parity-protected superconductor-semiconductor qubit, *Phys. Rev. Lett.* **125**, 056801 (2020).
- [20] M. Pita-Vidal, A. Bargerbos, C.-K. Yang, D. J. van Woerkom, W. Pfaff, N. Haider, P. Krogstrup, L. P. Kouwenhoven, G. de Lange, and A. Kou, Gate-tunable field-compatible fluxonium, *Phys. Rev. Appl.* **14**, 064038 (2020).
- [21] W. M. Strickland, B. H. Elfeky, L. Baker, A. Maiani, J. Lee, I. Levy, J. Issokson, A. Vrajitoarea, and J. Shabani, Gatemonium: A voltage-tunable fluxonium, *PRX Quantum* **6**, 010326 (2025).
- [22] J. Balgley, J. Park, X. Chu, E. G. Arnault, M. V. Gustafsson, L. Ranzani, M. Holbrook, Y. He, K. Watanabe, T. Taniguchi, *et al.*, Crystalline superconductor-semiconductor Josephson junctions for compact superconducting qubits, *Phys. Rev. Appl.* **24**, 034016 (2025).
- [23] N. Aparicio, S. Messelot, E. Bonet-Orozco, E. Eyraud, K. Watanabe, T. Taniguchi, J. Coraux, and J. Renard, Gate-tunable spectrum and charge dispersion mitigation in a graphene superconducting qubit, *Phys. Rev. Lett.* **135**, 266001 (2025).
- [24] A. D’Elia, F. Chiarello, D. Di Gioacchino, A. Piedjou Komnang, A. Giachero, C. Ligi, G. Maccarrone, F. Mattioli, C. Pira, A. Rettaroli, *et al.*, Coherent oscillations in weakly anharmonic NbSe₂ qubit, [arXiv:2509.17160](https://arxiv.org/abs/2509.17160).
- [25] D. Zoepfl, P. R. Muppalla, C. M. F. Schneider, S. Kasemann, S. Partel, and G. Kirchmair, Characterization of low loss microstrip resonators as a building block for circuit QED in a 3D waveguide, *AIP Adv.* **7**, 085118 (2017).
- [26] K.-L. Chiu, Y. Chang, A. J. Lasrado, C.-H. Lo, Y.-H. Chen, T.-Y. Hsu, Y.-C. Chen, Y.-C. Tsai, Samina, Y.-H. Lin, *et al.*, Integration of graphene-based superconducting quantum circuits in a three-dimensional cavity, *Phys. Rev. Appl.* **23**, 034059 (2025).
- [27] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/qtsh-154f> for details on device fabrication, the measurement setup and 3D cavity calibration, qubit-cavity detuning analysis for device 1 across cooldowns, coherence time (T_1 , T_2^*) measurements and analysis, HFSS/Maxwell simulations of the fixed-qubit coupling strength and capacitance in device 2, and additional power- and flux-dependence data for device 2 across multiple cooldowns, which includes Refs. [28–31].
- [28] D. R. Dean, Y. F. Young, I. Meric, C. Lee, L. Wang, S. Sorgenfrei, K. Watanabe, T. Taniguchi, P. Kim, S. L. Shepard, *et al.*, Boron nitride substrates for high-quality graphene electronics, *Nat. Nanotechnol.* **5**, 722 (2010).

- [29] A. S. Mayorov, R. V. Gorbachev, S. V. Morozov, L. Britnell, R. Jalil, L. A. Ponomarenko, P. Blake, K. S. Novoselov, K. Watanabe, T. Taniguchi, *et al.*, Micrometer-scale ballistic transport in encapsulated graphene at room temperature, [*Nano Lett.* **11**, 2396 \(2011\)](#).
- [30] S. J. Haigh, A. Gholinia, R. Jalil, S. Romani, L. Britnell, D. C. Elias, K. S. Novoselov, L. A. Ponomarenko, A. K. Geim, and R. Gorbachev, Cross-sectional imaging of individual layers and buried interfaces of graphene-based heterostructures and superlattices, [*Nat. Mater.* **11**, 764 \(2012\)](#).
- [31] J. Koch, T. M. Yu, J. Gambetta, A. A. Houck, D. I. Schuster, J. Majer, A. Blais, M. H. Devoret, S. M. Girvin, and R. J. Schoelkopf, Charge-insensitive qubit design derived from the Cooper pair box, [*Phys. Rev. A* **76**, 042319 \(2007\)](#).
- [32] L. Wang, I. Meric, P. Y. Huang, Q. Gao, Y. Gao, H. Tran, T. Taniguchi, K. Watanabe, L. M. Campos, D. A. Muller, *et al.*, One-dimensional electrical contact to a two-dimensional material, [*Science* **342**, 614 \(2013\)](#).
- [33] P. Krantz, M. Kjaergaard, F. Yan, T. P. Orlando, S. Gustavsson, and W. D. Oliver, A quantum engineer's guide to superconducting qubits, [*Appl. Phys. Rev.* **6**, 021318 \(2019\)](#).
- [34] A. Blais, R.-S. Huang, A. Wallraff, S. M. Girvin, and R. J. Schoelkopf, Cavity quantum electrodynamics for superconducting electrical circuits: An architecture for quantum computation, [*Phys. Rev. A* **69**, 062320 \(2004\)](#).
- [35] J. Gambetta, A. Blais, D. I. Schuster, A. Wallraff, L. Frunzio, J. Majer, M. H. Devoret, S. M. Girvin, and R. J. Schoelkopf, Qubit-photon interactions in a cavity: Measurement-induced dephasing and number splitting, [*Phys. Rev. A* **74**, 042318 \(2006\)](#).
- [36] M. Boissonneault, J. M. Gambetta, and A. Blais, Nonlinear dispersive regime of cavity QED: The dressed dephasing model, [*Phys. Rev. A* **77**, 060305\(R\) \(2008\)](#).
- [37] D. I. Schuster, A. Wallraff, A. Blais, L. Frunzio, R.-S. Huang, J. Majer, S. M. Girvin, and R. J. Schoelkopf, ac Stark shift and dephasing of a superconducting qubit strongly coupled to a cavity field, [*Phys. Rev. Lett.* **94**, 123602 \(2005\)](#).
- [38] L. S. Bishop, J. M. Chow, J. Koch, A. A. Houck, M. H. Devoret, E. Thuneberg, S. M. Girvin, and R. J. Schoelkopf, Nonlinear response of the vacuum Rabi resonance, [*Nat. Phys.* **5**, 105 \(2009\)](#).
- [39] X. Sun, B. Li, E. Zhuo, Z. Lyu, Z. Ji, J. Fan, X. Song, F. Qu, G. Liu, J. Shen, *et al.*, Realization of superconducting transmon qubits based on topological insulator nanowires, [*Appl. Phys. Lett.* **122**, 154001 \(2023\)](#).
- [40] G. Ithier, Manipulation, readout and analysis of the decoherence of a superconducting quantum bit, Ph.D. thesis, Université Pierre et Marie Curie—Paris VI, 2005.
- [41] S. Filipp, P. Maurer, P. J. Leek, M. Baur, R. Bianchetti, J. M. Fink, M. Göppl, L. Steffen, J. M. Gambetta, A. Blais, *et al.*, Two-qubit state tomography using a joint dispersive readout, [*Phys. Rev. Lett.* **102**, 200402 \(2009\)](#).